RIA Theory Bluebook: A Road Map

A Report from the RIA Theory Group

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Executive Summary

RIA theory covers a range of activities from nuclear structure and reactions, to the equation-of-state of nuclear matter. Nuclear science is also relevant to many processes in astrophysical environments. Since all nuclei heavier than carbon are made in stars, this synergy is, in fact, natural. Understanding both the basic nature of the nuclear many-body problem and understanding the effects of nuclear physics on stellar evolution and nucleosynthesis constitutes major intellectual challenge. Furthermore, low-energy nuclear science remains important in matters of national safety and security.

This document describes a number of theoretical challenges that must be met during the next decade in order to facilitate the success of an experimental program focused on short-lived isotopes. These efforts include:

- Development of ab initio approaches to medium-mass nuclei.
- Development of self-consistent nuclear density-functional theory methods for static and dynamic problems.
- Development of reaction theory that incorporates relevant degrees of freedom for weakly bound nuclei.
- Exploration of the isospin degrees of freedom of the density-dependence of the effective interaction in nuclei.
- Development and synthesis of nuclear theory, and its consequent predictions, into various astrophysical models to determine the nucleosynthesis in stars.

Present research facilities and projected upgrades to them, and the future RIA experimental facility, are measuring or will measure nuclear structure and reactions for nuclei that have very short half-lives and live close to the neutron (or proton) drip line. Many of these experiments will be relevant to astrophysics and will enable a comparison of theoretical predictions to experimental data. There will be numerous (in fact, many) nuclei and nuclear properties that we cannot measure. For an understanding of those systems, a robust nuclear-theoretical capability is required.

Certain critical investments in nuclear theory research over the last 10 years are yielding significant knowledge and understanding of properties of nuclei. Continued success will require investments in the following areas.

- Several approaches to the nuclear many-body problem have enabled both few- and many-body calculations to proceed in an ab initio way, starting from the basic two- and three-nucleon interactions. Critical investments for nuclear theory will include extensions of ab initio techniques to heavier nuclei and drip-line systems.
- Self-consistent mean-field theories offer a robust and global approach to a wide range of nuclei and nuclear properties. Critical to the success of this endeavor will be a full description of the energy-density functional, and the development of methods to treat excited states and giant resonances on the same footing.
- The treatment of the continuum in both structure and reaction theories has been, and will continue to be a critical area that requires both new ideas and new computational techniques in order to be successfully applied to reactions of nuclei near the drip-line.

- An understanding of the isospin dependence of the nuclear equation-of-state will be an important outcome of the medium-energy collision work performed at RIA. The theory community will also need to develop methods to extract relevant quantities from experimental data that will enable a description of the nuclear equation-of-state.
- The interplay of astrophysics and low-energy nuclear theory requires some level of coordination. This is taking place through two supernova SciDAC efforts for nuclear physics relevant to supernova production. We identified several other astrophysically interesting sites that would benefit from nuclear theory input.

While significant progress on the basic theoretical underpinnings of the nuclear many-body problem will require an enhanced workforce development and research effort, one challenge will be to export the knowledge gained from these research activities to the broader nuclear physics and nuclear astrophysics communities. One component of future research will be to assess the validity of models used in nuclear science applications (for example, in nuclear astrophysics), and that assessment hinges on our ability to perform calculations in ever larger nuclei and in nuclei far from stability.

We also identified several important areas and elements of theoretical nuclear astrophysics that should be actively supported. Each scientific area involves interdisciplinary challenges for both nuclear theory and astrophysics theory. Progress requires mutually beneficial and coordinated research in theoretical astrophysics and nuclear physics. This will allow us to combine leading-edge nuclear physics with the latest astrophysical models to answer the major open questions in nuclear astrophysics.

I. Overview of RIA Theory

Nuclear theory strives to build a unified and comprehensive microscopic framework in which bulk nuclear properties, nuclear excitations, and nuclear reactions can all be described. A new and exciting focus in this endeavor lies in the description of exotic and short-lived nuclei. The extreme isospin of these nuclei and their weak binding bring new phenomena to the forefront that will isolate and amplify important features of the nuclear many-body problem. This new arena of nuclei with large neutron excess is therefore key to building a unified theoretical foundation for understanding the nucleus in all its manifestations—from the stable nuclei that exist around us to the most exotic nuclei, and even to exotic forms of nucleonic matter which exist, e.g., in neutron stars. Nuclei also play key roles in stellar evolution and nucleosynthesis. Various nuclear properties and interaction cross sections are important ingredients in astrophysical simulations of stars, supernova, and nova.

RIA theory and associated experimental investigations will enable us to answer several long-standing questions in nuclear physics. These include understanding the following issues:

- *Changes in the effective nuclear interaction and the nuclear matter equation of state as a function of neutron excess:* What is the isospin dependence of the effective nuclear interaction? What is the density dependence of the effective interaction? How does one characterize the transition from finite nuclei to bulk nucleonic matter?
- *Foundations of independent particle motion:* How does shell structure change as a function of increasing neutron number? What is the role of the continuum in weakly bound nuclei?
- *Excitation and decay properties of weakly bound systems:* How does one quantify nucleon halos and skins in near-drip-line nuclei? What are the soft modes of excitation of these weakly bound systems?
- *Element production in the universe and the nuclear structures in stars:* What is the origin of the heavy elements in the universe? What role does nuclear structure play in supernovae explosion mechanisms? What are the properties of neutron stars?
- *Weak nuclear processes:* What are the nuclear uncertainties in fundamental symmetry measurements in atomic nuclei? How can unstable nuclei be used as laboratories for the fundamental symmetry tests?

Currently, a variety of nuclear research facilities within the United States, in Europe, and in Japan provide experimental data concerning the properties of both exotic and stable nuclei. In order to address astrophysical questions related to nuclear physics, the National Science Foundation (NSF) recently created the Joint Institute for Nuclear Astrophysics. In addition to the current U.S. facilities, efforts are ongoing to build the Rare Isotope Accelerator (RIA), the next-generation low-energy nuclear facility. RIA is a near-term, number-three priority project of the U.S. Department of Energy, Office of Science (and is the top priority within the Division of Nuclear Physics).

RIA and other exotic beam facilities allow unique insights into the quantum many-body nature of nuclei by providing access to their most extreme manifestations and by providing precise control of the number of nucleons in these systems. Recent theoretical and experimental achievements, coupled with the experimental discoveries that RIA will provide, are focusing new attention on a number of unsolved issues in nuclear structure and reactions, and offer excellent scientific opportunities for the next decade and beyond. Given the advent of research on radioactive nuclei, particularly with the coming of the RIA, it is extremely important to prepare nuclear theory for its realization. The RIA Theory Group consists of about 160 scientists who share the common purpose of moving theory forward to understanding the unique features of nuclei far from stability and related questions in nuclear astrophysics and mesoscopic physics.

The purpose of this RIA Theory Bluebook is to establish overall goals and strategies to meet the challenges of the RIA Theory Group in the coming years. In the following sections we discuss the scientific and societal ties that nuclear theory enjoys with other areas of science. We then turn to a detailed road map of required scientific developments that will enable the description of rare nuclei in the coming years.

II. Scientific Connections and Societal Impacts of RIA Physics

According to the 1999 National Research Council report on nuclear science titled *Nuclear Physics: the core of matter the fuel of stars,* low energy nuclear physics is “one of the cornerstones of the nation’s technological edifice”. Clearly, nuclear physics plays a major role in medicine, including modern imaging techniques, and the widespread use of radioisotopes for therapy and diagnosis. Furthermore, various nuclear properties are important to the stewardship of the nuclear stockpile and homeland security. Nuclei also play an extremely important role in our understanding of the universe around us. In fact, elements heavier than carbon were all made in stars. The nucleus shares common roots with other physical systems, where many-body quantum mechanics plays an essential role. Nuclear theory research also provides an excellent educational opportunity for the Nation’s highly technical workforce needs.

II.A. Intersections of nuclear physics and astrophysics

The physics of atomic nuclei governs the nature of most of the visible universe. Nuclear dynamics and structure are directly reflected in the nature of stars, the light curves of stellar explosions, and the abundances of chemical elements in the cosmos. Element abundance patterns produced by various nucleosynthesis events become increasingly important as tracers of large scale astrophysical processes such as galaxy formation. This will broaden the relevance of nuclear astrophysics for astronomy considerably. In addition many key questions in astrophysics such as the origin of the heavy elements, the physics of stellar explosions, nuclear and mixing processes in stars, the nature of compact objects such as white dwarfs and neutron stars and thermonuclear explosions on their surfaces, such as novae and X-ray bursts are directly linked to open questions in nuclear physics. This is particularly true for extremely unstable nuclei created in the extreme environments of stellar explosions and compact objects. With RIA we will be able to delineate experimentally the properties of many of these unstable nuclei for the first time. Simultaneously the next generation of astronomical observatories will provide data of unprecedented quality on element abundances and stellar explosions. This includes a next generation of more sensitive X-ray, few MeV γ-ray and optical telescopes, and also the large-scale spectroscopic surveys, like SEGUE in the SLOAN-II and emerging multi-object fiber-optics systems together with refined analysis methods of star dust, for example from meteorites. Continuing advances in nuclear theory, theoretical astrophysics, and computational astrophysics will enable a unified interpretation of these new data and give an understanding of the nuclear processes in nature that ultimately are responsible for our existence.

A close collaboration between nuclear physics and astrophysics will therefore maximize the impact of RIA science. The experimental results of RIA must be interpreted in terms of nuclear theory and then be incorporated into astrophysical simulations to be translated into astrophysical observables that can be directly compared with telescope data. This requires that new experimental and theoretical nuclear physics data are merged with existing data into an evaluated and documented data archive for nuclear astrophysics. At the same time new observations and their astrophysical modeling needs to be considered when prioritizing the RIA nuclear physics program.

II.B. Connections to neutrinos and fundamental symmetries

Nuclear theory advances during the next decade will significantly impact research programs associated with searches for physics beyond the Standard Model. Experimentally, RIA promises to generate a great variety of radioactive isotopes with high intensities that will provide unprecedented opportunities to search for physics beyond the Electro-Weak Standard Model. For example, RIA will allow for orders-of-magnitude improvements on limits of the CP-violating atomic Electric Dipole Moment (EDM) and on the determination of the Weinberg angle from measurements of parity violation in Fr atoms. New measurements of β−decay using ion or atom traps will produce much higher precision for searches for non V-A contributions to the weak interaction. Finally, β-decay measurements, coupled with new information on the spectroscopy and masses of the appropriate nuclei far from stability, could provide definitive information on the apparent nonunitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

The research portfolio in nuclear physics also encompasses neutrino-nucleus interactions and the search for neutrino properties. One of the central questions in neutrino science today concerns whether the neutrino is its own antiparticle. The recent discovery that neutrinos oscillate and have a finite (albeit small) mass makes neutrino science an interesting area of discovery that will require nuclear theory input for its interpretation. For example, if a $0\nu\beta\beta$-decay experiment sees a definitive signal, then experimentally we would understand that neutrinos are Majorana particles with a definite mass. There is no other realistic way to determine the nature (Dirac or Majorana) of massive neutrinos. Furthermore, precise theoretical knowledge of the nuclear $0\nu\beta\beta$-decay matrix element would allow us to interpret the neutrino mass spectrum. Thus, advances in nuclear theory will be crucial to the success of a neutrino science program.

II.C. Connections to mesoscopic systems

The scientific community is witnessing the birth of a new area of physics that will supplement traditional macrophysics of large systems and physics of the micro-world, namely mesoscopic physics. This name can be applied to systems that are sufficiently large to display generic statistical regularities but at the same time sufficiently small to allow the researchers to study in detail, theoretically and experimentally, individual quantum states. The future successes of fundamental physics and technology are in the direction of mesoscopic systems, such as atomic and metal clusters, complex molecules including fullerenes and biological molecules, quantum dots and nanoscale solid state devices, Bose and Fermi gases in atomic traps, and the elementary units (qubits) of future quantum computers.

Although on a much shorter length scale, nuclei are also prototype mesoscopic systems. Mesoscopic systems display a variety of common phenomena. For instance, shell structure, collective surface excitations, and pairing and superfluidity are found both in nuclei and in other mesoscopic systems like atomic clusters, quantum dots, small metallic grains, and trapped atom gases. On the one hand, nuclear theorists have made important contributions to the theory of mesoscopic physics when applying their expertise to these nanoscale problems. On the other hand, nuclear theorists are also employing techniques and methods that originated in other fields of physics. This cross-fertilization generates vitality and yields an appreciation of nuclear theory outside the field. RIA physics offers several opportunities for interdisciplinary research. Some broad categories of com-mon problems are outlined in the following.

The transition from microscopic to mesoscopic to macroscopic - The general challenge for theory of mesoscopic systems is to understand the principles of building up complexity out of "elementary" blocks, which in fact have a complicated structure of their own, similar to how quantum chemistry builds complex molecules, including biological, of simpler atoms. RIA data will challenge theory to explain how increasingly complex nuclei are build from protons and neutrons. Heavy and super-heavy nuclei form a bridge between nuclear drops and nuclear matter similar to what can be studied in nanoscience.

Loosely bound and open systems - RIA will produce loosely bound nuclei that will require theoretical advances in the physics of marginally stable and open systems that are tied to those needed for negatively charged molecules, and quantum wires and other solid state micro-devices.

Coherent phenomena - Collective excitations and the coherent response to external fields play a crucial role in all mesoscopic systems. New examples of collective modes will be presented by RIA. Superfluidity, shape transformations, shape coexistence, and other quantum phase transitions, which will be encountered in new forms in nuclei far from the valley of stability, will require new approaches, possibly close to those used for atomic clusters, metallic grains, and ultra-cold Fermi gases. We definitely need a much deeper understanding of thermodynamics and precursors of phase transitions in finite systems.

It is necessary to continue the study of quantum chaos with interplay of one-body and many-body effects common for complex nuclei and quantum dots and vitally important for future quantum computers.

Quantum transport - Quantum transport is another topic of general interest. In energetic central reactions of heavy nuclei, the nuclear medium gets excited and its density is increased compared to that normal for nuclei. Under those circumstances, the de Broglie wavelength of nucleons becomes comparable to the nucleon mean-free path, signifying the quantum nature of nucleon transport across the reaction zone. The mesoscopic character of the transport is further underscored by the fact that the interaction range becomes comparable to the mean-free path. The method of non-equilibrium Green's functions developed for nuclear physics has been adapted and expanded to semi-conducting devices, memory effects, plasmas and decay through barriers in conjunction with dissipation. Overall, with regard to this difficult topic, a synchronized effort is needed, with any significant development impacting different areas simultaneously.

II.D. Connections to computational sciences

The entire field of low-energy nuclear physics and nuclear astrophysics utilizes resources available to perform large-scale calculations. The definition of 'large-scale' changes each year as raw computational power increases: today it is common for various theoretical projects to use tens of Teraflop-hours of computing time per month in order to solve some of our current problems. Computational efforts in the field will grow, and it is important to take advantage of the new generation of machines that will become available. As examples, we mention Green's Function Monte Carlo for nuclei, neutron drops, and nuclear matter, no-core shell model for nuclei and effective operators, coupled-cluster theory for nuclei, shell-model Monte Carlo studies of medium-mass nuclei, HFB calculations of mass tables, hydrodynamic and transport codes that probe the nuclear equation of state, and multidimensional core-collapse supernova simulations (requiring nuclear theory input). These computational problems are just a few examples of the rich variety of theory that can utilize the large-scale technology available for scientific computing.

The revolution in scientific computing technology will continue its torrid pace over the next few years, and nuclear theory must take advantage of the resources available. The challenges will be to provide numerical algorithms that scale across hundreds to thousands of processors. This involves rethinking common algorithmic structures. For example, in the last few years Lanczos algorithms have become efficiently developed for parallel application; nuclear coupled-cluster theory has recently been developed with scaling in mind. Quantum Monte Carlo algorithms are naturally parallel and have taken significant advantage of parallel machines. SciDAC funds two efforts in supernova simulations (including nuclear structure components), and the field should continue to take advantage of this funding stream when appropriate.

Many of the future directions discussed in section III will be tied to continuing advances in high-performance computing. Our field should take the time and effort required to develop efficient numerical algorithms that will scale to large processor numbers since these algorithms will allow us to pursue far more science than would otherwise be possible.

II.E. Relevance to National Security

The mission of the Stockpile Stewardship Program is to determine the reliability and safety of the aging nuclear weapons stockpile without recourse to a resumption of nuclear testing. Although that mission uses a variety of techniques to accomplish its goals, the experimental basis representing the "ground truth" for all of the techniques is the suite of data collected during the era of underground nuclear testing. Much of that data was obtained using "probes", i.e., known amounts of stable isotopes, which were placed near a device before it was exploded. The amounts of isotopes present in the post-explosion debris were then measured. In principle, the comparison of the isotope abundances before and after gives information about the performance of the device – using a detailed physics description of what happens to isotopes in the extreme environment of intense fluxes of neutrons and X-rays. This physics description may be incomplete (and perhaps inaccurate) because most of the intermediate processes occurring during this extremely rapid transformation have never been measured and the theoretical models that were used in the past to describe these reactions were limited. In all, these processes involve very short-lived isotopes, which will be the domain of experimental program at RIA. As in the case of the r-process, while experiment may be preferable, it is unlikely that every nucleus in the reaction chains will be amenable to experiment, and improvements to theoretical models will be essential. Overall, a combination of improved experiment and theory will permit the calibration of the probes to an impressive new level of accuracy, which in turn would improve the data from the nuclear test suite as well as the confidence in the accuracy of that data.

Another concern is how to deal with the detonation of a terrorist nuclear device. A portion of this problem falls under the rubrics "Nuclear Forensics" and "Attribution". The issue is the ability to examine the debris following such an unthinkable event and to determine the source of the device. As with Stockpile Stewardship, the accuracy of the models to do this attribution work depends sensitively on the knowledge of the intermediate processes on short-lived species present during the explosion. Experiments at RIA and substantially improved theoretical models are needed to improve the accuracy (and specificity) of these attribution efforts.

III. RIA Theory Detailed Road Map: Goals and Strategies

In this chapter, we discuss a detailed road map that will enable progress toward rare nuclei. The key components in moving forward involve placing the nuclear many-body problem on a more firm footing, and increasing the number of degrees of freedom that can be investigated in nuclear reaction models, thereby decreasing the parameterizations used, and identifying key low-energy nuclear physics input to astrophysics. We organize this section according to various sub-fields, recognizing that efforts in several of the fields actually overlap.

III.A. Nuclear structure

Atomic nuclei are extraordinarily interesting quantum many-body systems that exhibit a diverse range of phenomena. While comprised of a very limited number of particles, nuclear structure manifests both individual particle dynamics as well as collective dynamics at the same energy scale. Remarkably, although nuclei have been the object of intense study for over 70 years, the ability to execute, theoretically, the conceptually simple task of "building" a nucleus up from its constituent parts, the protons and neutrons, has yet to be fully realized. This is largely due to the complex nature of the interaction between constituent nucleons and the solution of the quantum many-body problem. The leading two-nucleon interaction is characterized by a strong short-range repulsion and strong spin and isospin components. In addition, there is now mounting evidence that three-body forces significantly affect nuclear structure. For the most part, because of these complexities, progress in nuclear structure theory has largely relied on approximate methods of solutions with effective interactions renormalized to experimental data. While largely successful, this approach is unsatisfying, as the renormalizations are essentially based on approximations, and extrapolations into regions where experimental data are absent, as will be the case for RIA, have uncertainties that are not quantifiable. The goal of nuclear theory in the future must be to go beyond it empirical roots, and to arrive at a fundamental understanding of nuclear properties from a unified theoretical standpoint rooted in the fundamental forces between nucleons.

Our overarching goal for the future is to ground our approaches within the fundamental interactions between nucleons, whether we utilize bare interactions in ab initio calculations, effective interactions in large-scale microscopic calculations, or applications of density functional theory for mean-field treatments.

Goal: **Comprehensive description of nuclei and nuclear matter rooted in a fundamental understanding of the inter-nucleon interactions.**

III.A.1. Develop ab initio structure and reaction theory

A long-standing goal in nuclear physics has been an exact treatment of nuclei utilizing the fundamental interactions between nucleons. Due to the advent of new theoretical techniques and exceptional improvements in computational capabilities, this goal is finally beginning to be realized in light nuclei. The prospects look bright, and it is likely that within the next decade, exact results for medium-mass nuclei may be attained. With these powerful new methods and a full determination of inter-nucleon interactions, it will be possible to explore the rich diversity of properties exhibited in light nuclei, such as clustering phenomena, deformation, the locations of the proton and neutron drip lines, neutron halos, and low-energy nuclear reactions important for stellar physics.

The starting point is the nuclear Hamiltonian. Much work has been done to explore the properties of the nucleon-nucleon interaction, and today several high-quality versions derived from nucleon-nucleon scattering and the properties of the deuteron are available. These range from local potential models such as Argonne V18 to non-local interactions based on meson exchange, such as CD-Bonn, and QCD-based interactions derived within the framework of effective field theory. It is well known that all of these high-quality two-nucleon interactions fail to reproduce the binding energy of even the simplest complex nuclei, namely the three-body system, and that three-body interactions are required. While three-nucleon interactions provide a modest amount of binding, about 6% to the total binding energy, there is mounting evidence that spin-orbit and isospin-dependent components in the three-body interaction strongly affect the structure of nuclear levels and even the location of the drip line. All realistic nucleon-nucleon interactions that reproduce the scattering phase shifts predict the wrong ground state for ^{10}B. The stronger spin-orbit components in three-nucleon interactions can correct not only this deficiency, but also strongly modify the amplitudes of transition operators, such as Gamow-Teller.

Three-nucleon interactions are also required to adequately describe the binding energy changes in an A-chain as one increases the proton-neutron difference towards the drip line. Progress towards a complete ab initio description of nuclei, including those near the drip lines, requires a full understanding of the two- and three-body components of the nuclear interaction. Many of the features of the three-nucleon interaction are manifested in many-body nuclear systems. Consequently efforts to determine the full form of the inter-nucleon interactions must go hand-in-hand with solutions to the many-body problem.

To date, several complementary methods have been employed in ab initio studies. The most successful has been the Green's Function Monte Carlo (GFMC), which is now providing "exact" results for ^{12}C including both two- and three-nucleon potentials. A serious first attempt has been made to determine the full form of the three-nucleon interaction by examining its effects on the structure of nuclei. Shown in Figure 1 is the current state-of-the-art GFMC method for p-shell nuclei up to ^{12}C. The results obtained so far are impressive, and a full determination of the three-nucleon force and its effect on nuclear structure will likely be determined in the coming years. Going beyond ^{12}C with the current formulation, however, is computationally difficult, and algorithm changes may be required. One possibility is to utilize the Hubbard-Stratonovich transformation on the quadratic spin and isospin operators in the imaginary-time propagator. While this method may significantly reduce computational requirements and permit calculations of heavy nuclear systems, it is unclear if the sign-problem, which is endemic in Monte Carlo applications to fermion systems, can be overcome.

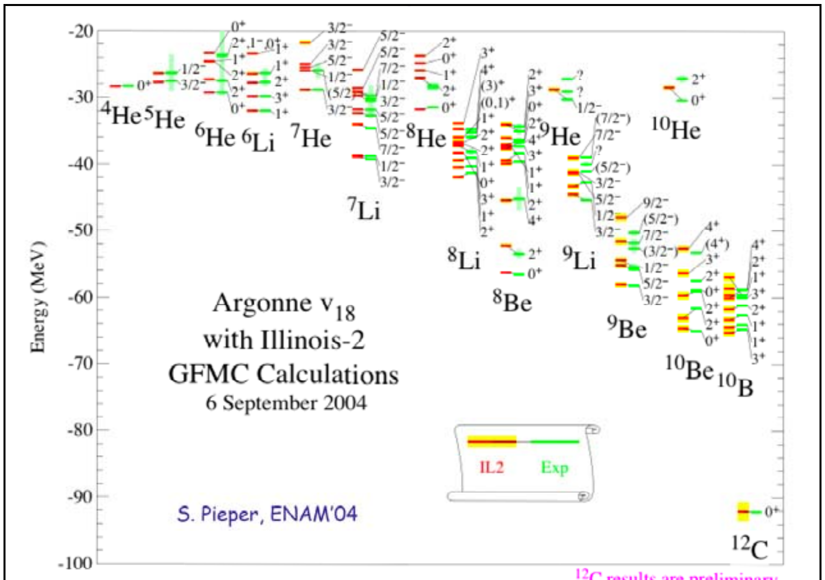

Figure 1. Comparison of the state-of-the-art GFMC results utilizing realistic NN interactions and the Illinois-2 three-nucleon potential with experiment for levels in p-shell nuclei up to ^{12}C.

A complementary approach is the No-Core, Shell Model (NCSM), which is based on the application of effective-interaction theory within the context of the shell model. A key feature of the NCSM is that because of the separation between the allowed and excluded spaces, the effective interaction has two-, three-, up to A-body components even if the Hamiltonian is only two-body in character. In this context, convergence to exact results can be achieved by increasing the number of clusters included in the effective interaction and/or by increasing the size of the allowed space. The NCSM can also provide a bridge to heavier nuclei by giving important guidance on the nature of effective interactions that can then be used with other "conventional" many-body approaches such as the shell model. Another promising method for ab initio studies is the coupled-cluster technique. An advantage of coupled-clusters is that it is a size-extensive method that can provide very accurate results in many-body systems.

In the coming decade, ab initio studies of nuclear structure will continue, and key questions, such as the nature of the nuclear Hamiltonian, level ordering, Gamow-Teller transition amplitudes, root-mean square radii, and clustering will be answered. In addition to the rich diversity of structure exhibited in the light p-shell nuclei, their reactions have important consequences for the fate of the universe. Indeed, low-energy fusion reactions are the primary energy generation mechanism for stars, and help determine the course of stellar evolution. Further, much of what we know about neutrino oscillations is determined from neutrinos emerging from the Sun following the beta decay of reaction products and, in particular, ^{8}B. If solar neutrinos are to provide even more precise information on the oscillation properties, the light-ion fusion rates comprising the standard solar model need to be improved. Structure also plays an important role in these reactions. Perhaps the most complex and most important astrophysical reactions are the fusion of three alpha-particles to form ^{12}C, and the fusion of ^{12}C nucleus and an alpha-particle to form ^{16}O. Both fusion reactions are dominated by the contributions of resonances and/or subthreshold states. Here, ab-initio description of the structure of these states in the many-body framework is a formidable challenge. Here, an ab initio description of the structure of these resonances in the many-body framework is a formidable challenge. Indeed, presently a fundamental description of coupling reaction mechanisms with nuclear structure has yet to be realized. An important goal for the next decade will be to extend the ab initio efforts into a fundamental reaction formalism that will be capable of accurately calculating reaction cross sections, break-up reactions, and the alpha-capture reactions leading to the production of ^{12}C and ^{16}O in stellar environments.

Wonderful insight into the in-medium properties of protons in nuclei has been obtained from extensive studies of the (e,e'p) reaction. Most experimental efforts have been geared towards successfully establishing absolute spectroscopic factors of valence protons in closed-shell nuclei. Recently, a complete picture has emerged from NIKHEF and JLab experiments detailing the exploits of the other protons in the nucleus. These protons partially occupy deeply bound orbits of the shell model while high-momentum protons have been identified as the signature effect of short-range correlations associated with the core of the bare inter-nucleon interaction. Successful efforts have recently been launched at NSCL to extract neutron spectroscopic factors opening the study of the dynamics of the shell model to neutron-rich and, in general, more exotic nuclei. Such experimental results will become available for truly exotic nuclei with RIA. The prime theoretical tool to study these nucleon properties in the medium is the Green's function method. Recent developments geared to nuclear physics include the incorporation of the Faddeev technique to include particle-particle and particle-hole collective effects at low energy in the nucleon self-energy. The Green's function method can be used as an ab initio approach in heavy nuclei, since it does not generate wave functions but transition amplitudes and therefore requires less numerical effort. Green's function techniques should answer the fundamental question how the in-medium properties of nucleons change when extreme values of neutron to proton ratios are encountered. The influence of the continuum will need to be included in these calculations.

III.A.2. Develop an understanding of the nature of effective interactions and operators used in nuclear structure models

Typical large-basis shell-model calculations, which are some of the most successful detailed microscopic descriptions of nuclei, start with an effective interaction derived for a given shell-model space. Experience shows that while a derived effective interaction is a good starting point, agreement with experimental data is often lacking. At this point, the effective interaction is then empirically tuned to experimental data. Changes with respect to the original effective interaction are usually small; however, the exact nature of these changes is not known. While applications have generally been successful, the fact remains that calculations carry with them an uncertainty that is difficult to quantify. This is particularly true for extrapolations to nuclei outside the region where the Hamiltonian has been empirically determined. Furthermore, without a more formal approach to these effective interactions, it is difficult, if not impossible, to determine an effective interaction that would be applicable to new regions of nuclear structure, where data do not yet exist.

With any truncation of the active model space, not only do we have an effective interaction, but each and every operator must also be renormalized, leading to effective operators. The general procedure has been to be guided by theoretical formalism; however, to determine effective charges, g-factors, etc., one requires that they reproduce known experimental data. Again, we have the situation where the nature of the renormalizations is not well understood.

Concurrent with developing a more formal mechanism to determine the effective interaction is the ability to utilize them while including the relevant degrees of freedom. While the computational challenges incurred in microscopic models can be daunting, the methods often provide rich rewards, leading to an increased capability to manage an ever larger number of many-body basis states. In addition, Monte Carlo sampling of shell-model basis states has also proven to be successful, and solutions that can be reliably extrapolated to the exact result can be obtained for nuclei in the middle of the fp-shell region, where the number of basis states exceeds 2 billion. Factorization methods, truncations based on symmetry groups, and density-renormalization group methods may also prove successful in extending detailed microscopic calculations to nuclei not thought possible before.

The nature of effective interactions and operators is critical to the study of nuclear structure. It is vital to note that the effective interaction is determined by the choice of the active Hilbert space, and formal theories based on realistic inter-nucleon interactions, or effective field theories need to be formulated. While promising approaches exist (for example, similarity transformations to the active Hilbert space, or ladder summations, etc.) they do not yet fully incorporate the realistic three-body interaction. This issue is particularly important in the next decade (prior to the advent of RIA) where detailed nuclear theory studies of nuclei away from the valley of stability will be carried out, and some degree of confidence and certainty (hopefully quantifiable) can be achieved.

III.A.3. Develop predictive density-functional theory for nuclei and nuclear matter

Density functional theory (DFT) is built on theorems showing the existence of universal energy functionals for many-body systems, which include, in principle, all many-body correlations. Condensed matter physicists and computational chemists have developed such functionals for the Coulomb interaction that describe properties of a wide range of systems with chemical accuracy.

In nuclear physics, self-consistent methods based on the DFT, e.g., the Hartree-Fock-Bogoliubov theory with Skyrme parameterizations, have achieved a level of sophistication that allows analyses of experimental data for a wide range of properties and for arbitrarily heavy nuclei. A recent example is shown in Figure 2, where HFB calculations were used to explore the rich physics exhibited by super-heavy nuclei.

The achieved accuracy and predictive power of mean-field calculations, however, still leaves much to be desired. This is illustrated in Figure 3, where two-neutron separation energies for Sn isotopes resulting from Hartee-Fock-Bogoliubov calculations utilizing a wide range of Skyrme potentials are shown. On the left, the comparison with present experiment can be quite good. However, each of the various Skyrme potentials extrapolates to different results as one advances to the neutron drip line where data do not exist to constrain theory. The quest for a truly universal DFT of nuclei, including dynamical effects and symmetry restoration, is one of the main themes of theoretical nuclear structure worldwide.

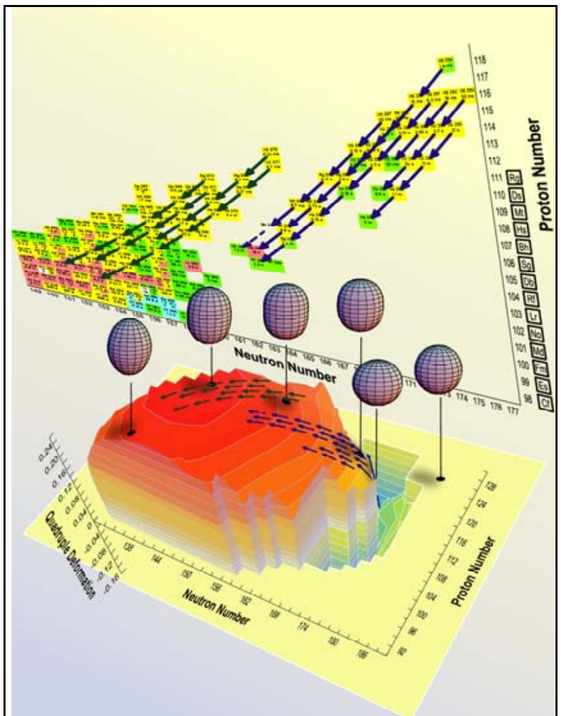

Figure 2. Deformations and shapes for the heaviest nuclei calculated in the Skyrme HFB model The Z=110-113 alpha-decay chains found at GSI and RIKEN (green arrows) go through prolate shapes (red-orange) while the Z=114-118 chains reported at Dubna (blue arrows) start in a region of oblate shapes (blue-green). The nuclear chart in the super-heavy region courtesy of S. Hofmann (GSI).

We believe that a concerted effort rooted in a fundamental understanding of inter-nucleon interactions offers promise to achieve corresponding qualitative improvements in the accuracy and applicability for nuclear physics. Current functionals lack a sufficient understanding of density and isospin dependences and an adequate treatment of many-body correlations, which are required for robust and controlled extrapolations to low densities, large asymmetries, and higher temperatures. New challenges not generally faced by Coulomb DFT are the essential roles of symmetry breaking and pairing, and the need for symmetry restoration in finite, self-bound systems. The functional should have a solid foundation based on microscopic inter-nucleon interactions with an ultimate goal of quantitative matching to microscopic theory (as in Coulomb DFT). Addressing these challenges will require us to exploit advances in the study of microscopic inter-nucleon interactions, in the development of many-body computational techniques, and in raw computer power, as well as to further develop DFT itself as applied to finite, self-bound systems.

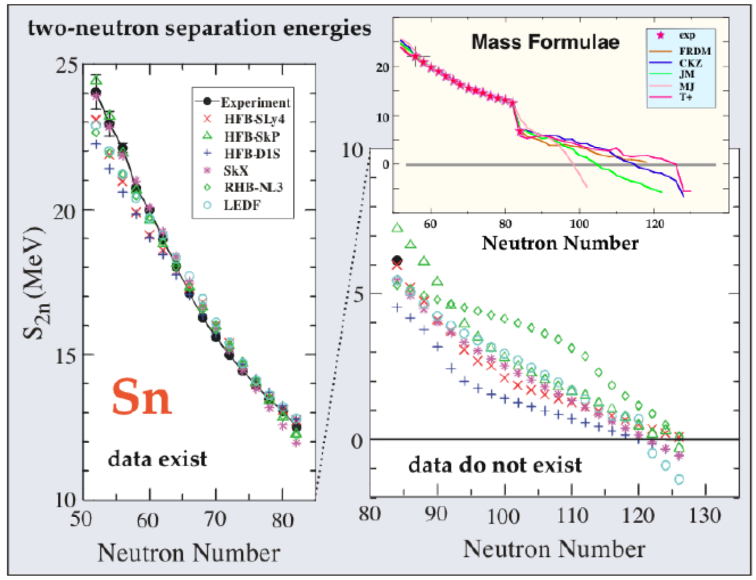

Figure 3. Comparison of two-neutron separation energies obtained from Hartree-Fock-Bogoliubov calculations utilizing several Skyrme potentials. On the left-hand side a comparison is made with experimental data. On the right, the calculations are extended towards the neutron drip line.

The first, most general question to be addressed is just what is the form of the nuclear energy-density functional? Limitations of current functionals in describing isovector and density dependences reflect both insufficient constraints from data (e.g., for time-odd fields) and incomplete physics encoded in the functionals.

To make progress, a concerted effort will be required to study new functionals when applied to finite nuclei and infinite or semi-infinite nuclear matter. For instance, in the particle-hole channel, one would like to enrich the density dependence of the effective mass in order to differentiate between its value in the bulk and at the Fermi surface. Another goal is to understand connections between the symmetry energy and isoscalar and isovector mean fields, and in particular the influence of effective mass and pair correlations on symmetry energy versus isospin. Such an understanding will allow us to better determine isospin corrections to nuclear mean fields and energy density functionals. In the self-consistent method, the average nucleonic field is obtained from the nucleonic density. Consequently, in the nuclear state with nonzero angular momentum, the self-consistent potential acquires time-odd components. These terms are expected to play a significant role at very high angular momentum when the nucleus is strongly polarized, but they should also influence properties of beta decay and the ground states of odd-mass and odd-odd nuclei.

Fundamental questions, such as constraints on the most general form for functionals and the existence of DFT for intrinsic densities, need to be addressed. Effective field theory (EFT) methods, now widely applied for few-nucleon systems, can provide systematic insight into the density dependences along with error estimates.

Little is known about the basic properties of the pairing force. Up to now, the microscopic theory of the pairing interaction has only seldom been applied in realistic calculations for finite nuclei. A "first-principles" derivation of the pairing interaction from the bare NN force still encounters many problems such as, e.g., the treatment of core polarization. Hence, phenomenological density-dependent pairing interactions are usually introduced. It is not obvious how the density dependence should be parametrized, although nuclear-matter calculations and some experimental data (e.g., isotope shifts and odd-even mass staggering) suggest that pairing is strongly affected by the nuclear surface. This is why neutron-rich nuclei play such an important role in this discussion. Indeed, because of strong surface effects, the properties of these nuclei are sensitive to the density dependence of pairing. The investigation of the density and isospin dependence of pairing interactions is a significant part of this program.

A better understanding of the symmetry energy appears to be a key element in resolving the question of the proton-neutron (p-n) pairing. The isoscalar p-n pairing is our current best explanation for the additional binding of N=Z nuclei, the so-called Wigner energy. However, basic questions regarding the collectivity of such a phase still remain unanswered.

Spontaneous symmetry-breaking effects are at the heart of the mean-field description of highly correlated many-body systems. A large part of those correlations can indeed be included by considering symmetry-breaking product states. Within the mean-field approach, one can understand many physical observables by directly employing broken-symmetry states; however, for finite systems, a quantitative description often requires symmetry restoration. For this purpose, one can apply a variety of theoretical techniques; in particular, projection methods and the generator-coordinate method.

Ideally, one would like to work out approximations that would allow avoiding full-scale collective calculations, but would be based on calculations performed on top of self-consistent mean fields. In this way, we hope to develop the microscopic mass formula in which both the mean-field mass and the dynamical corrections would be obtained from the same energy-density functional. In this context, it is important to note that the realistic energy-density functional does not have to be related to any given effective force. This creates a problem if a symmetry is spontaneously broken. While the projection can be carried out in a straightforward manner for energy functionals that are related to a two-body potential, the restoration of spontaneously broken symmetries of a general density functional poses a conceptual dilemma that has not yet been properly addressed.

Finally, a reliable extrapolation to unknown nuclei is possible only with the establishment of theoretical error bars. Consequently, construction of new energy density functionals should be supplemented by a complete error and covariance analysis. It is not sufficient to just "predict" the properties of exotic nuclei by extrapolating from a DFT determined by reproducing experiment. It is also necessary to quantitatively determine errors related to such an extrapolation. Moreover, for experimental work, it is essential that an improvement gained by measuring one or two more isotopes be quantitatively known. From a theoretical perspective, it is important to arrive at the confidence level with which the parameters of the functional are determined.

III.A.4. Develop many-body theories of nuclear collective dynamics, including the large amplitude collective motion and nuclear decays

To achieve a consistent description of nuclear excitations in open-shell super-conducting nuclei, one has to go beyond the static mean-field approximation. A powerful tool for understanding small amplitude collective motion (both for low-lying collective states and giant resonances) is the quasi-particle random-phase approximation (QRPA). For weakly bound nuclei, an important extension to the standard treatment involves a proper treatment of the particle continuum. Continuum extensions are usually carried out in coordinate space, which facilitates the treatment of decay channels and guarantees the correct asymptotic behavior.

Recently, fully self-consistent QRPAs have been developed and a limited number of studies have been carried out to address properties of exotic nuclei such as electromagnetic strength, nature of individual collective states, decay properties, and electroweak processes. The main challenge is the inclusion of symmetry-breaking effects associated with shape deformations and pairing in the presence of strong coupling to the particle continuum. Once a deformed QRPA framework is developed, the whole range of open-shell, neutron-rich nuclei will open up for exploration.

While QRPA investigations are useful for small-amplitude motion, large amplitude collective motion, which drives fission, fusion, cluster decay, shape coexistence, and phase transitions, provides a particularly important challenge. These phenomena involve the mixing of mean fields with different symmetries. The transition from one stable mean field to another goes through one of several level crossings around which the original symmetry of the system is broken. We have yet to obtain a microscopic understanding of large-amplitude collective motion that is comparable to what we have for ground states and small-amplitude collective motion.

One possible approach to large-amplitude collective motion is time-dependent extensions to the static mean-field solutions of Hartree-Fock or Hartree-Fock-Bogoliubov. While time-dependent Hartree-Fock theory has been well developed and employed, particularly in the 1970s and 1980s, its application to exotic nuclei has not been extensively undertaken. Extensions to include the self-consistent pairing field have never been fully developed except in adiabatic approximations to the full theory.

Another useful microscopic tool that extends the applicability of mean-field methods to excited states, and potentially to large-amplitude collective motion, is the Generator-Coordinate Method (GCM). The GCM wave function is usually taken as a combination of many (projected) intrinsic states calculated self-consistently within constrained mean-field theory. The GCM wave function is rich enough to accommodate correlations absent in the mean field and is not limited to the adiabatic regime. Moreover, GCM is based on the variational principle. Applications of GCM face both numerical and conceptual challenges. First among these is the choice of generator coordinates, which are usually selected in an arbitrary way that depends on the problem and our physical intuition. Second, many problems, such as fission or cluster decay, require the use of several collective degrees of freedom and an immense computational effort. Third, it is not clear how to apply GCM to weakly bound nuclei with nearly vanishing chemical potentials. Finally, there are fundamental problems with incorporating GCM into density-functional theory.

Spontaneous fission is one the oldest decay modes known, but is still not fully understood. It represents one of the most extreme examples of large-amplitude collective motion: the tunneling of a many-body system. Here, the pairing interaction plays a substantial role because it leads to a dramatic smoothing of single-particle crossings, thus improving the adiabatic approximation. Many calculations of spontaneous fission (lifetimes, sometimes mass/charge splits) are based on the adiabatic assumption. While the majority of calculations have used microscopic-macroscopic methods, very few self-consistent applications have been performed in the adiabatic limit.

We also need to develop the microscopic foundation of popular phenomenological models of collective excitations, such as, for example, interacting boson model and other group-theoretical approaches, and understand the physics underlying their success and deficiencies in description of nuclear spectra and shape phase transitions. This is important in connection to diversity of shapes and deformations possible in exotic nuclei.

III.A.5. Develop unified treatment of bound states and open channels

A major theoretical challenge in a full microscopic description of nuclei, especially weakly bound ones, is the rigorous treatment of both the many-body correlations and the continuum of positive-energy states and decay channels. The importance of the continuum for the description of resonances is obvious. Weakly bound states cannot be described within the closed quantum system formalism since there always appears a virtual scattering into the continuum phase space involving intermediate scattering states. A unified description of excited states in weakly bound nuclei and reactions on weakly bound nuclei (described more fully in Sections III.B.1 and III.B.2.) is one of the main goals of modern nuclear structure physics.

One possible strategy of tackling the continuum challenge is by use of the resonant-state expansions, e.g., the Berggren ensemble that consists of Gamow (or resonant) states and the complex non-resonant continuum. Since these theories incorporate continuum states into the single-particle basis they can be used for a microscopic description of halo nuclei, particle-unstable nuclear states, reactions of astrophysical interest, and a variety of nuclear structure phenomena. Initial applications in light isotopes are proving successful. The main challenge is to develop a realistic effective interaction that will enable us to address physics of weakly bound nuclei such as ^{11}Li. Other major problems are the treatment of the center of mass, the inclusion of anti-bound states, and the handling of very large shell-model spaces. The successful application of continuum shell models to heavier nuclei is ultimately related to the progress in optimization of the many-body basis, which is related to the inclusion of the non-resonant continuum configurations. One promising development is the adaptation of the density matrix renormalization group method to the problem in which continuum states are a part of the basis.

The recently developed approach using the effective non-Hermitian Hamiltonian is another promising direction with the advantage of a simultaneous description of bound states, threshold phenomena, and reaction cross sections for the long isotope chains.

The Gamow-state technology has also been applied to spherical and deformed proton emitters. In particular, a nonadiabatic coupled-channel method has been developed that properly takes into account the Coriolis coupling due to the rotational motion of the deformed daughter nucleus. Using this model, one obtained a consistent description of deformed proton emitters, including proton lifetimes and branching ratios (fine structure in proton emission). The weak point of the current approaches to the phenomenon of proton emission is a very crude treatment of pairing. To remedy this deficiency, the Berggren ensemble can be utilized to solve the HFB equations. This will allow us to efficiently take into account continuum effects and particle or quasiparticle resonance states. Such a description is practically impossible in the harmonic oscillator basis, and requires a huge numerical effort in the coordinate representation, especially for deformed systems.

III.B. Nuclear reactions

Reactions are the major tool in the study of unstable nuclei. Reliable theoretical reaction descriptions are crucial in order to enable accurate extraction of the desired structure information. Due to the astrophysical motivation, further understanding of drip line properties requires data at lower energy, where many reaction approximations are not valid. The interplay between reaction and structure is unanimously recognized as a prime element for a successful model.

There are several important challenges presented to reaction theory: the one particle and two particle continuum known to be essential in the description of reactions of drip-line nuclei need to be handled consistently; four body dynamics should be treated exactly in many cases; core excitation needs to be taken into account; and we are lacking a unified approach to the fusion of drip-line nuclei. Many of these challenges connect to computational issues.

Goal: Develop a unified approach to reaction theory that provides for a reliable interpretation of the variety of measurements that will be performed at RIA.

III.B.1. Understand the essential role of intermediate and final continuum states in reactions with weakly bound and exotic nuclei

Continuum states are necessarily populated when nuclei near the drip lines are involved in reactions. We discussed in Section III.A.5 their importance in the description of the structure of weakly bound nuclei. How these states contribute to reaction mechanisms needs to be understood for the description of a wide variety of experimental data. This, in turn, will yield reliable structure information from experimental data. We discuss in the following paragraphs a variety of issues that will require focused research in the coming years.

Intermediate continuum states play a role during particle transfer, either as excitations of a weakly bound participant (such as a deuteron or a nucleon in a halo nucleus) or as transfers from such participants to the well-Q-matched low-energy continuum in the other participating nucleus. The continuum may be in a deformed system. If transfer reactions such as (d,p) are to be used to determine single-particle structures, then virtual breakup in the deuteron channel must be taken into account. Developments along these lines are in progress and will continue.

Both virtual and real continuum states play an essential role in moderating the fusion of weakly bound nuclei, where there is a competition between loss of flux from real breakup and attractive polarization potentials from virtual breakup. These must both be understood on an equal quantum footing in order to reliably predict the production yields of exotic nuclei by fusion mechanisms (see III.B.4).

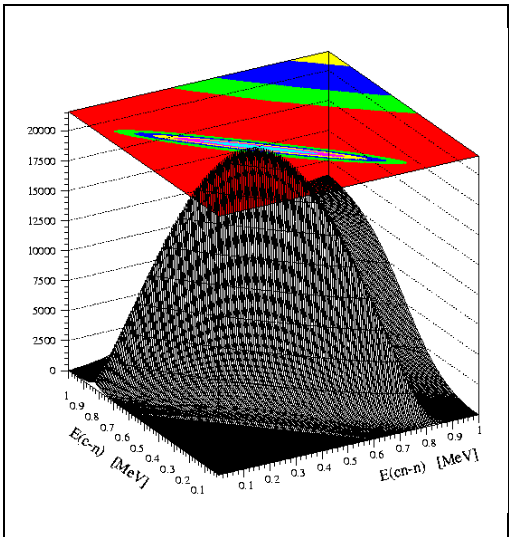

Figure 4: Single-particle energy correlations in the quadrupole 2+ resonance in ^{6}He

Near the drip lines, one often finds nuclei with valence nucleons so loosely attached that their wave density is distributed as a halo around a central core nucleus. Often these halo nucleons appear as pairs as in ^{11}Li. For example, in two-neutron transfer reactions involving the projectile ^{6}He (which behaves like a three-body system consisting of an alpha particle and two neutrons), the sequential transfer proceeds through the intermediate continuum states of ^{5}He. One challenge involves including all the necessary dynamics of the two-nucleon halo projectile into transfer reaction models.

Predictions of detailed observables are needed for comparison with rare isotope experiments. For knock-out reactions, analysis relies on theories of elastic and inelastic breakup (diffraction dissociation and stripping). More powerful stripping experiments yield both integrated cross sections and momentum or angular distributions. A great need exists for theoretical developments that will enable us to understand, predict, and analyze such distributions.

III.B.2. Extend reaction models to include the dynamics of two-particle continuum

Due to the dominance of the 0s channel in the nucleon-nucleon interaction, *pairing* plays an essential role in nuclear structure. However, extraction of nuclear-pairing information from experimental data is nontrivial. Reaction theory must be developed so that it can be used to describe pairing in the context of experimental data. As the drip line is approached, pairing becomes more clearly delineated in nuclear structure (e.g., for the Borromean systems mentioned above), and becomes completely visible from data either at higher scattering energies, or beyond the drip line. Reaction theory that properly treats pairing must treat the bound and

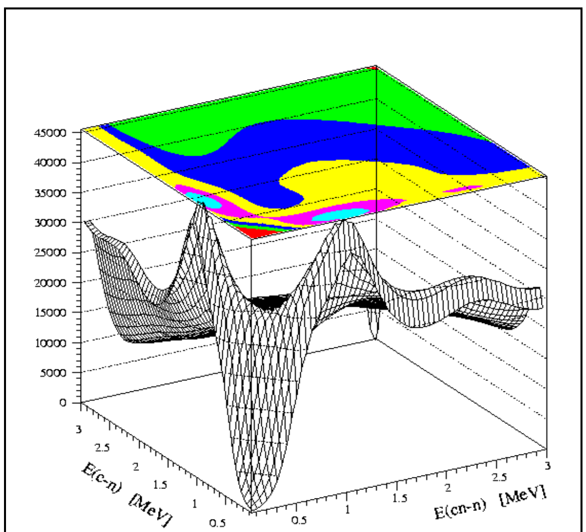

Figure 5: Single-particle energy correlations in the 1- dipole continuum in ^{6}He

continuum pairing states in a consistent framework. Most importantly, one needs a clear mapping between pairing fields calculated from mean-field theory and the appearance of real nucleonic pairs available for transfer or breakup. Also, the correlations of two particles (neutrons or protons) near threshold, such as in halo nuclei, in both spherical and deformed systems need to be isolated from other effects. Models for two-nucleon breakup states must include all dynamical correlations such as two- and three-body resonance states, two-body bound subsystems, and non-resonant states. Finally, the excitation mechanism for two-nucleon states in RIA reactions needs to be explored as a function of scattering energy. Theories will have to go beyond both first-order and impulse approximations and will need to treat to all orders the many dynamical rearrangements possible for paired nucleons in the continuum.

III.B.3. Incorporate new structure information in peripheral reaction models of collective and/or valence nucleon transitions

An essential tool for extracting structure information involves peripheral reactions on the nucleus of interest. Recent efforts focused on developments of reaction theory that extend to drip-line nuclei. Required advances in reaction theory applications will enable descriptions that extend beyond the separation energy prescriptions for bound states and transitions in nuclei. One path forward involves including microscopic structure information in reaction theory. This includes calculations of single-particle state transitions taken from the No-core Shell Model (see Section IV.A) instead of the approximate single-particle transitions that are present in standard reaction codes. In the same spirit, nucleon overlaps and coefficients of fractional parentage calculated using Variational Monte Carlo or Greens Function Monte Carlo methods should replace the single-particle wave functions whenever feasible. One usually describes collective behavior in reactions with vibrational/rotational models. These semi-classical models should be significantly enhanced by inclusion of microscopic descriptions of transition densities for collective excitations. One useful path forward employs quasi-particle RPA models of nuclear level densities. An important development will be to map the quasi-particles onto the densities of real nucleons. Furthermore, transfer states for nucleons derived from mean-field theory with pairing will also benefit from a mapping of the quasi-particles and pairing densities onto physical nucleonic densities.

III.B.4. Improve the microscopic structure in cluster reaction models

Cluster models are useful tools to describe collective behavior in light nuclei, in particular alpha clustering, which most microscopic models fail to produce. Microscopic cluster models treat Fermi antisymmetrization and various nuclear symmetries exactly. They assume the existence of cluster states described in a simple microscopic way and determine quantum mechanically the wave functions of their relative motion. The treatment of reactions occurs as a natural extension. Applications of cluster models to astrophysical capture reactions at low energies are particularly successful. The main limitation of the microscopic cluster models is related to the simplified effective NN interactions that allow the clusters to have reasonable energies and radii. Improving the forces implies improving the internal description of the clusters. Ultimately, in the age of advanced computation, previous approximations should be lifted: the cluster model should advance into an ab initio theory of reactions between light nuclei. For instance, it is known that the effects of tensor and three-body forces are required for a good description of the physical properties of the clusters. Improved, but tractable, cluster wave functions consistent with these forces must be derived.

Given the success of cluster models in nuclear astrophysics, improvement on the accuracy of astrophysical S factors for transfer and capture reactions previously studied should be obtained by combining ab initio descriptions of bound and scattering states.

III.B.5. Develop theoretical techniques to extract reaction rate information from indirect methods

The Coulomb barrier strongly hinders measurements of low-energy astrophysical reaction rates. For this reason, researchers developed indirect experimental techniques to extract rate information more accurately. These techniques include the Coulomb Dissociation, Asymptotic Normalization Coefficient (ANC), Trojan horse and surrogate methods. In the Coulomb dissociation technique, a breakup reaction in the Coulomb field of a heavy target is measured and then related to the inverse capture reaction. In the ANC method, one uses transfer reactions to extract the asymptotic normalization coefficient of the relevant ground state wave function (the final state of the capture reaction), which, in turn, determines the necessary astrophysical direct capture rate at zero energy. The trojan horse method relies on measurements of cluster-transfer reactions where a part of the incident nucleus act as a spectator. The surrogate technique is an indirect method where a direct-reaction is used to populate a compound system and decay probabilities for various channels are measured and combined with theoretical models to infer the cross sections for the reaction of interest. These indirect methods are based on one-step simplifications of the reaction amplitude. In the last few years, the effect of Coulomb-nuclear interference, as well as continuum multi-step effects and other higher-order processes, were shown to be relevant, particularly in weakly bound nuclei, making the extraction of the desired astrophysical information less transparent and precise. Optimal observables that allow for a clean extraction of the astrophysical information need to be identified.

Recent improvements of the accuracy of the direct-capture measurements have revealed a serious discrepancy between the direct and the indirect methods. These discrepancies must be elucidated.

III.B.6. Develop theoretical methods that describe fusion of heavy nuclei

Fusion processes generate compound nuclei which then decay by emission of gamma-rays and potentially by boiling off neutrons. Complete fusion of light elements is responsible for energy generation in stars, and is the experimental mechanism used to generate super-heavy nuclei. Fusion is a dynamical process governed by quantum mechanics and involves single- and multi-nucleon tunneling through complicated barriers. Fusion is strongly affected by nuclear shell effects and deformation. The actual theoretical description of such processes is not satisfactory. Indeed, the different phenomena participating in fusion, such as the coupling of different reaction channels, polarization, reorientation, tunneling, and dissipation, make the theoretical description problematic. Different avenues should be followed to address this problem.

One approach involves the application of the coupled-channels technique, which can take into account many open or virtual channels, possibly with one or several particles in the continuum. This method should be further developed to treat complex fusion processes. Also crucially important to address are conceptual difficulties associated with differentiating complete from incomplete fusion, as well as numerical issues in current coupled-channels calculations including the continuum.

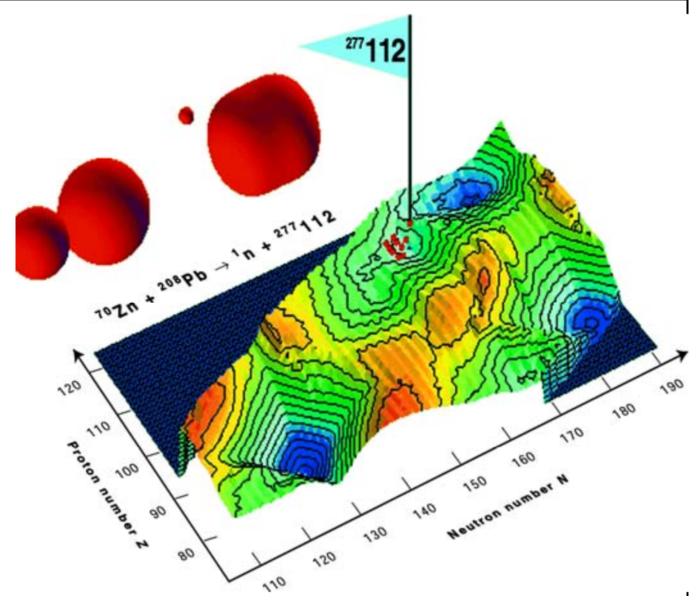

Figure 6: Production probabilities for heavy and super-heavy nuclei after one-neutron evaporation in a Zn+Pb fusion reaction

As discussed in Section III.C.2, a practical implementation of quantum transport theory will benefit all reaction studies, including fusion, where other descriptions are less successful. In particular, the extension of time-dependent approaches that go beyond the mean-field limit, and take into account nuclear correlations should be explored.

In the meantime, progress is expected from extensions of semi-classical treatments such as the Langevin approaches by including more collective degrees of freedom, and from partial studies targeting a specific aspect of the fusion reaction such as the reorientation, the polarization, the break-up, etc. Of particular interest is the role of the neutron haloes and skins, and, in a more general context, the role of the isospin dynamics in the fusion process.

III.C. Nuclear matter equation of state

Isospin represents a fundamental quantity in nuclei and nuclear matter. The third component of isospin measures the imbalance between neutrons and protons in a given system. The liquid-gas phase transition in a two-fluid asymmetric nuclear matter has some distinct new features compared to that in the symmetric matter behaving as one fluid. For example, the coexistence region shrinks with a reduced critical temperature. Furthermore, the liquid and the gas phases present a different asymmetry leading to an isospin fractionation or “distillation". The asymmetry term in the free energy drives both phenomena. Studies of the isospin dependence of the nuclear phase diagram thus enrich our understanding of the EOS of asymmetric matter.

Goal: Extract isospin dependence of thermal, mechanical and transport properties of nuclear matter in nuclei, neutron stars, and supernovae.

III.C.1. Develop statistical approaches to phase transitions and cluster formation in asymmetric nuclear matter

Most features and results of the liquid-gas phase transition can be successfully described by statistical approaches. Only a few global variables in reactions leading to the liquid-gas phase transition have to be described dynamically, as demonstrated by molecular dynamics and transport model simulations.

To extend existing statistical and thermodynamic approaches to the liquid-gas phase transition and to cluster formation in asymmetric matter, theoretical efforts in several directions must be explored. From the conceptual point of view, development of a statistical description of transient, finite, and open unbound systems based on information theory and the characterization of phase transitions should be pursued focusing on two-fluid systems. The role of the long-range non-saturating Coulomb force must be investigated. From the nuclear physics point of view, statistical multi-fragmentation models need to include more information from nuclear structure studies on the masses and binding energies of nuclei near neutron and proton drip lines. Furthermore, critically important is better knowledge of the isospin dependence of level density parameters for hot nuclei. With these improvements, statistical approaches to be developed for the liquid-gas phase transitions in asymmetric matter should be also useful for describing phase transitions and cluster formation in some astrophysical situations.

III.C.2. Develop a quantum transport theory for complex reactions

In energetic central reactions of heavy nuclei, the nuclear medium becomes excited and its density increases relative to that of normal nuclei. Under these circumstances, the de Broglie wavelength of the nucleons becomes comparable to the nucleon mean-free path, signifying the quantum nature of nucleon transport across the reaction zone. The importance of the quantum nature of the nucleon dynamics is reinforced by the uncertainty principle which imposes a strong delocalization of the nucleons. The role of the isospin degree of freedom needs to be investigated within the framework of quantum transport theories including sufficient many-body correlations and dynamical fluctuations. Such theories would enable us to accurately study the origin of measurable isospin effects and directly relate them to the properties of underlying nuclear interactions. The challenge is to implement practical quantum transport theories that reduce to an ab initio theory in the limit of sufficient computing power and/or few-body systems.

One avenue of future research utilizes a non-equilibrium Green's function approach at the 2-body level. This approach yields a practically viable time-dependent density matrix. A further important task involves the incorporation of the impressive developments in electronic quantum transport applied to nanostructures in semi-conducting devices.

Quantum transport theories may also be developed by improving existing semi-classical transport theories that are very successful in studying many aspects of heavy-ion reactions. One possibility would be to follow a stochastic extension of mean-field theories in which the one-body distribution experiences a stochastic evolution in response to the action of a fluctuation term. The amplitude of this term is related to the stochastic nature of the nucleon-nucleon and also incorporates thermal effects. Another approach is by further developing the antisymmetrized quantum molecular dynamics (AMD) model to include collective dynamics associated with its matching to mean-field theory.

III.C.3. Identify the role of isospin degree of freedom in the dynamics from peripheral to central reactions

The isospin degree of freedom plays an essential role in nuclear reactions via both the initial state and the reaction dynamics. Besides those reaction observables sensitive to the asymmetry term of the EOS, it is particularly important to identify the role of isospin degree of freedom in specific processes which we specify below.

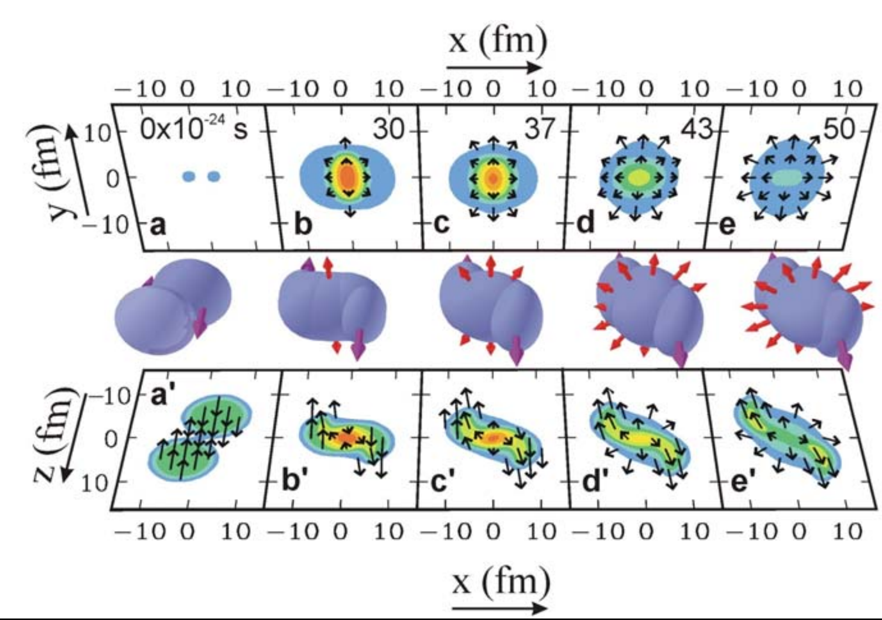

Figure 7. Overview of dynamics for an energetic b=6fm Au+Au collision from the Boltzmann equation. Time increases from left to right. The 3-dimensional surfaces in the middle panels represent a constant density $\rho \sim 0.1\rho_0$. Bottom panels show contours of constant ρ in the reaction (x-z) plane. The outer edge there represents $0.1\rho_0$ and the color changes show steps of $0.5\rho_0$. Back panels display contours of constant transverse pressure in the x-y plane, in steps of 15 MeV/fm^3. Arrows indicate the average velocities at selected points.

Competition between various reaction mechanisms occurs in central collisions. We need to identify the interplay of low-energy dissipative mechanisms, e.g. fusion (incomplete) vs. deep-inelastic vs. neck fragmentation. A stiff symmetry term in the EOS leads to a dynamics characterized by more repulsion between nuclei. Also, we need to model fusion dynamics in the presence of a large charge asymmetry in the entrance channel. A dynamical prompt dipole radiation is expected (and observed even in stable ion collisions) to be of great interest as a cooling mechanism along the fusion path.

In addition, fragmentation in semi-peripheral reactions at the Fermi energies needs to be studied. An interesting neutron enrichment of the overlap (“neck”) region is expected, due to the migration of neu\(spectator regions) to lower (neck) density regions. This effect is sensitive to the density dependence of the symmetry energy.

The early stage of the reaction dynamics between neutron-rich nuclei needs to be understood. Pre-equilibrium particle emissions and collective flows appear particularly sensitive not only to the density but also to the momentum dependence of the interaction. In asymmetric matter the splitting of neutron and proton effective masses due to the non-locality and/or relativistic structure of isovector interactions is expected. The sign of the splitting is quite controversial. Hence, it is very important to extract information on this fundamental question from nuclear collisions. One can use probes, such as pre-equilibrium particles, that are particularly sensitive to the high-density phase.

The relationship between the nuclear mean field and nucleon-nucleon cross sections needs to be made more explicit. In reactions above the Fermi energies, the isospin degree of freedom influences the dynamics through the symmetry potential, isospin-dependent nucleon-nucleon cross sections, and the Pauli blocking. The isospin dependence of in-medium nucleon-nucleon cross sections is predicted to be weaker than that in free-space. Since both the time scale and magnitude of isospin transport are affected by the in-medium nucleon-nucleon cross sections, some observables, such as the isospin diffusion and neutron-proton differential flow, can also be used to extract information about the isospin-dependence of in-medium nucleon-nucleon cross sections. A crucial theoretical challenge is to calculate consistently all isospin-related ingredients used in describing the reaction dynamics from the same nuclear effective interactions.

Finally, all these phenomena require a strong simulation effort in order to assess their sensitivity to the effective force, EOS, and transport properties.

III.C.4. Determine observables constraining the equation of state and phases of asymmetric matter from sub- to supra-normal nuclear densities

RIA provides a unique opportunity to pin down the isospin-dependent part of the EOS of asymmetric matter, specifically, the density dependence of the symmetry energy. A set of observables has been promising as EOS probes and should be studied thoroughly.

Thus, the n-to-p ratio at large energies and probably also spectra and yields of hard photons from the (n,p) bremstrahlung in central reactions, are sensitive to the density and momentum dependence of the symmetry potential. The energetic particles are expected to stem from the high-density zone formed early on in a reaction. The symmetry potential is expected to affect relative emission times for neutrons and protons accessible through the n-p correlation functions. The neutron and proton scattering from nuclei with widely varying n-p imbalance, studied as a function of energy, and possibly the charge-exchange reactions, can constrain the potential at subnormal and normal densities.

Isotopic yields of Intermediate Mass Fragments (IMF) in central collisions satisfy an approximate scaling relationship, with an exponential coefficient constraining the symmetry energy at the time of fragment emission. Correspondingly, from the scaling, one leans both on the symmetry energy and on the conditions at emission. The characteristics of midrapidity IMF from semicentral collisions have been further suggested for probing the symmetry energy, and among those, the correlations between different fragment N/Z ratios, masses, and alignment.

Transport of isospin across a reacting system is sensitive to both the density and momentum dependence of the symmetry potential, with the potential providing a driving force. A particularly promising probe for the features of the potential at high density and excitation is the differential n-p flow quantifying the different accelerations that neutrons and protons are subjected to. Finally, ratios of charged pions, produced in NN collisions, can reveal features of the symmetry energy at high densities. A stiff symmetry energy, larger at high ρ, will lead to fewer π^-, relative to π^+, than a soft symmetry energy. Studies of effects for mesons with smaller rescattering effects, such as subthreshold kaons, would be desired.

III.D. Nuclear astrophysics

We identify six astrophysical sites where close collaboration between nuclear physics and astrophysics will maximize the impact of RIA science. These are stars in general, core-collapse supernovae, white dwarf supernovae, compact stellar objects together with their associated explosive surface layer phenomena such as X-ray bursts and novae, and the s-process in low-mass giant stars.

Nuclear theory is needed to transform the data from RIA into a comprehensive theoretical understanding of the physics of unstable nuclei. The experimental results of RIA must be interpreted in terms of nuclear theory and then be incorporated into astrophysical simulations to be translated into astrophysical observables. This requires that new experimental and theoretical nuclear physics data are merged with existing data into an evaluated and documented data archive for nuclear astrophysics. This path will maximize the scientific impact of RIA on astrophysics as it allows one to go far beyond the straightforward implementation of directly measured data into astrophysical models. For example, using theoretical models, one can derive astrophysically important quantities such as reaction rates from indirect measurements in the many instances where a direct experiment is not possible. Furthermore, this approach will enable us to reliably predict the subset of relevant nuclear properties that cannot be measured - either because they are beyond the capabilities of even RIA, or because they come only into play at the extreme temperatures and densities in the astrophysical environment. This includes charged-particle-induced reaction rates, which have to be extrapolated to the low astrophysical energies using theoretical reaction models. For most astrophysical applications, nuclear theory is required that leads to the development of accurate global models that can be applied efficiently to all nuclei instead of attempting to understand the physics of just a particular nucleus or reaction. We identify here the nuclear theory efforts that are necessary to maximize the impact of RIA experiments on progress in nuclear astrophysics.

Goal: Understand the origin of heavy elements, the physics of stellar explosions, nuclear mixing processes in stars, the nature of compact objects, and thermonuclear explosions on their surfaces.

The consequences of such a new understanding of element production and the required nuclear physics output must then be explored in astrophysical models and theories. We identify those aspects of astrophysical theories that are intimately related to the RIA experiments, and we also identify those parts that simply comprise the larger astrophysical context. For example, multi-dimensional core-collapse supernovae simulations form the larger context, while r-process post-processing calculations of such supernova models will maximize RIA science return. Astrophysics theory is also needed to help prioritize and plan RIA nuclear astrophysics experiments. For example, sensitivity studies can identify the critical nuclear physics in astrophysical models. Such studies require estimates of uncertainties for experimental and theoretical nuclear data.

III.D.1. Understand nucleosynthesis in the first generation of stars

Although stars have been unambiguously identified as the cauldrons of the nuclides with mass numbers of 12 or larger, many questions about the origin of the elements in the Universe remain still unanswered. During their hydrostatic burning stages, stars generate their energies from nuclear reactions producing new elements up to the zinc mass range.

Of particular current importance is the question of the nucleosynthesis in the first generation of stars. The formation and evolution of these stars is closely linked with the properties of the first cosmological structures that emerged after the Big Bang, and with the onset of reionization of the Universe. Most valuable information about the many unknown processes that played a role in that era is contained in the spectroscopic abundance data of the most metal-poor stars. Such stars are now being discovered and many more will be found in future, much more powerful spectroscopic surveys. An example is SEGUE, part of the Sloan Digital Sky Survey (SDSS) extension, that will identify 35,000 candidate stars with ultra-low metallicity (UMP stars). Nuclear astrophysics is needed to decipher the unique information contained in the abundance patterns of these stars, which serve as probes for the properties and evolution of the first stars and their cosmological environment. Abundances determined in UMP stars are particularly important, as they provide nucleosynthesis information on a single supernova event or a superposition of very few nuclear production sites, possibly also including intermediate mass stars. This is in contrast to the solar system abundance distribution, which is a convolution of numerous nucleosynthesis sites that are sometimes difficult to disentangle.

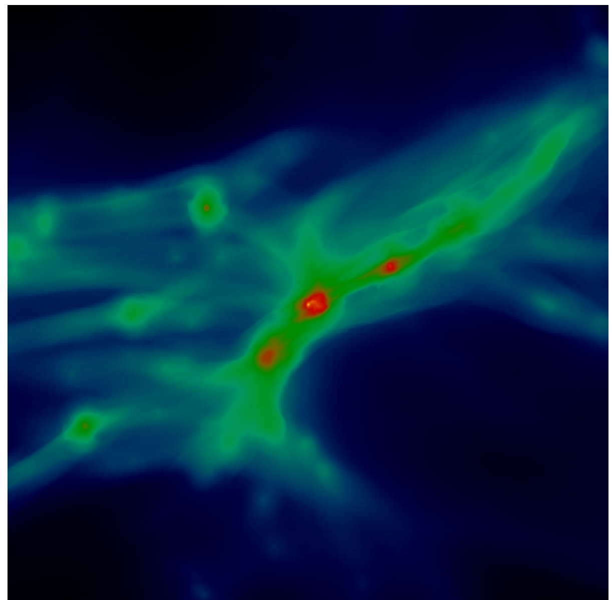

Figure 8. Distribution of baryonic matter clustering around the cosmological dark matter halo. The projection volume of ~1.5 proper kiloparsecs on a side is centered on the halo where the first population III star in this region will form. This halo is surrounded by other halos in which the second generations of primordial and/or metal-enriched stars will form.

Integrated simulations taking into account both structure formation and nuclear production in the early universe will lead to predictions of abundance patterns of the most metal-poor stars that can be compared with spectroscopic data. These studies will also clarify the nuclear physics needed to understand the underlying nucleosynthesis processes peculiar to the first generation of stars. However, the modeling of stellar evolution and the associated nucleosynthesis requires the knowledge of many reaction cross sections which, at stellar conditions, usually cannot be directly measured in the laboratory and hence require some extrapolation procedure of data. The theoretical models used for these extrapolations have to be improved, advancing them to tools based on a microscopic description of the reaction partners and dynamics.

III.D.2. Develop quantitative nuclear microphysics for core-collapse supernova to understand the explosion mechanism and the origin of the heavy elements

The nuclides produced inside of massive stars are ejected into the interstellar medium by cataclysmic events involving the collapse of the stellar inner core and the subsequent ejection of the outer stellar shells. The general picture of such core-collapse supernovae is well accepted; however, current models are still sensitive to the details, and slight variations in the codes change a successful explosion to a fizzle. To obtain quantitative supernova models, theorists must explore multidimensional effects, detailed transport effects, and adequately incorporate all relevant physics. Simultaneously, the underlying nuclear physics needs to be understood. While gravity is the energy source for supernovae, neutrinos mediate this energy, and nuclear physics will play a major role in transforming the core collapse into an explosion. Challenges for nuclear theory include the calculation of electron captures on nuclei at extreme conditions, neutrino-nucleus interactions, the neutrino opacity of nuclear matter, and the equation of state at finite temperatures and high density.

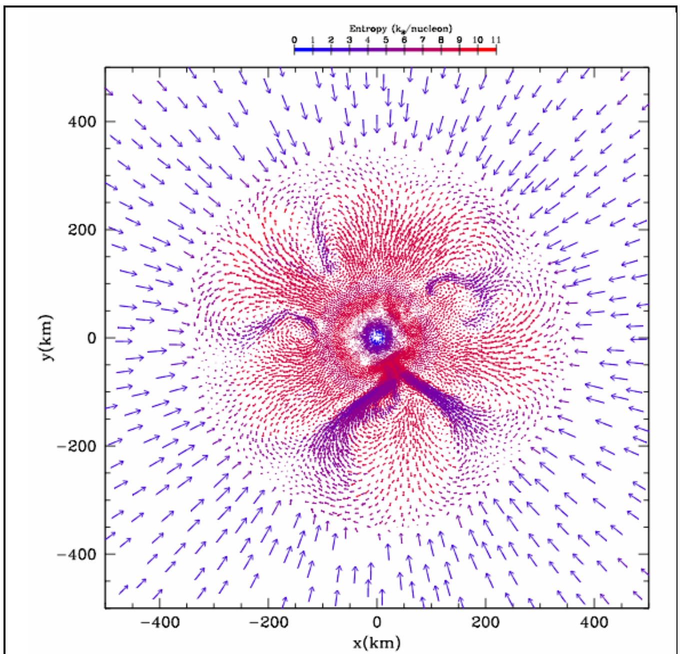

Figure 9: Matter flow in a 3-D core collapse supernova simulation.

During supernova explosions, the abundances of the nuclides produced in the hydrostatic burning stages are modified and new elements are produced. It is one eminent goal to simulate nucleosynthesis consistently following all phases of hydrostatic burning and explosion. Besides improved stellar models and the development of successful supernova models that take into account the observed asymmetries of the explosion, this requires the coupling of a large nuclear network to the supernova models involving numerous reaction rates, many of which have to be predicted by theory.

A particular important case of explosive nucleosynthesis is the p-process, which is responsible for the origin of the most proton-rich stable isotopes in nature in the mass range from selenium to mercury. A likely site for the p-process is the supernova shock front passing through the envelope of a dying star triggering (γ,n), (γ,p), and (γ,α) photodisintegration reactions on stable and unstable nuclei. P-process model calculations rely heavily on reaction-rate calculations using statistical models, in particular for reactions involving unstable nuclei. These models require accurate descriptions of level densities and nuclear potentials.

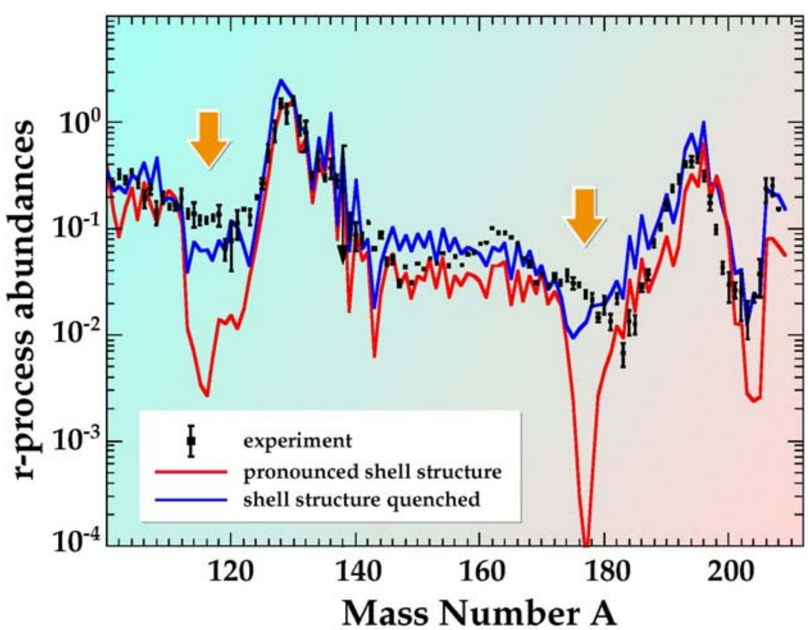

Figure 10: Observed heavy element abundances in the solar system that originate from the r-process together with two attempts (red and blue) to model r-process nucleosynthesis. Both models are based on the same astrophysics and differ only in assumptions on the nuclear shell structure far from stability.

Neutrinos play a crucial role for the supernova dynamics and nucleosynthesis. The neutrino spectra have to be reliably calculated as a function of space-time, including their generation by weak-interaction processes on nuclei (electron captures, beta-decays), and their transport through the hot and dense matter, and potentially invoking neutrino flavor oscillations. The emitted supernova neutrino spectra are predicted to exhibit a characteristic energy hierarchy between the various neutrino types. It is the goal to observe these differences with dedicated detectors from a future galactic supernova.

Upon leaving the star, neutrinos can also leave fingerprints by producing certain elements via neutrino-induced nucleon spallation off nuclides in the outer stellar shells. The abundance of specific elements can serve as neutrino thermometers and put constraints on oscillation parameters once the physics of neutrino-nucleus interactions is well understood.

The rapid neutron capture process (r-process) is responsible for the synthesis of about half of the stable nuclei heavier than iron. As it requires extremely high neutron densities, it is most likely connected to explosive astrophysical sites. Currently, the r-process site or sites are unknown, and different scenarios related to supernova explosions and neutron star mergers are discussed and actively investigated. New, accurate observations of r-process elements in stars expected from ongoing and planned astronomical campaigns, as well as the solar r-process abundance pattern, are the only way to directly constrain the conditions at the r-process site and might hold the key to the solution of the r-process problem. The interpretation of abundance observations in terms of r-process conditions requires the understanding of the underlying nuclear physics of extremely unstable neutron-rich nuclei. RIA represents a major step in this quest, making a significant fraction of the nuclei in the r-process accessible to experiments for the first time. However, even with RIA, there are r-process nuclei that remain out of reach, and even for the ones that are accessible, not all relevant properties can be measured in all cases. This includes neutron capture rates on unstable nuclei that can only be measured indirectly, for example, using (d,p) transfer reactions or Coulomb breakup. For the interpretation of such measurements, reaction models that can be applied to heavy r-process nuclei need to be developed. In addition, theoretical corrections for the extreme astrophysical environments during the r-process are needed, such as theoretical predictions of capture and decay rates on thermally populated excited states. Therefore, progress in the understanding of the nuclear physics of the r-process requires a concerted effort in experiment and theory. The challenge is to develop global models that capture nuclear structure changes far from stability and therefore have predictive power for heavy nuclei towards the neutron drip line. What needs to be calculated are neutron separation energies, half lives, neutron-capture cross sections, beta-delayed neutron emissions, beta-delayed and neutron-induced fission probabilities and fragment distributions. Since the r-process might occur at sites with extreme neutrino fluxes, neutrino-induced total and partial spallation and fission cross sections have to be calculated. It will be important to find ways to characterize the possible theoretical uncertainties so as to be able to judge the significance of possible differences between r-process models and observations.

Developing realistic multi-dimensional hydrodynamic models of core-collapse supernovae comprises the larger astrophysical context which addresses open questions such as the explosion mechanism and asymmetries. What is specifically needed to enhance the RIA science output is to develop core collapse simulations, explosive nucleosynthesis calculations, and r-process post-processing calculations of the multi-dimensional thermodynamic trajectories of the supernova simulation that incorporate all relevant nuclear physics. This will transform the results from RIA into astrophysical predictions that can be compared with observables. Besides core-collapse supernovae, alternative sites for the r-process, in particular for secondary weaker r-processes, need to be explored astrophysically. This is a prerequisite for determining the nuclear physics that is relevant for such scenarios and needs to be identified in time to guide the RIA experimental effort.

III.D.3. Understand the nucleosynthesis of thermonuclear supernovae

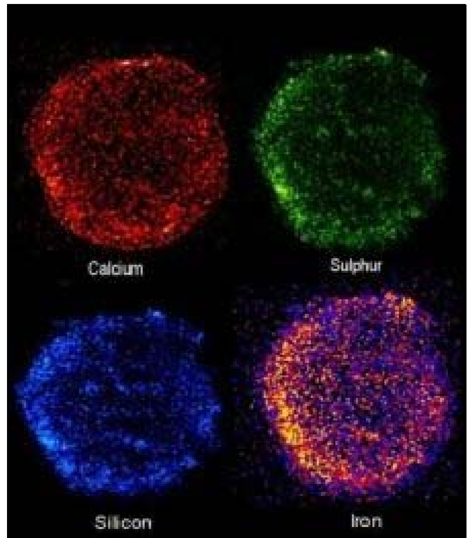

Figure 11: Element distribution observed in Tychos remnant of a type Ia supernova (ESA)

Thermonuclear supernovae, observationally classified as Type Ia, are of key importance to astrophysics and cosmology. They represent extremely bright standard candles used to probe cosmological distances and the acceleration of the universe. They are also an important source for nucleosynthesis, mainly elements around iron. Type Ia supernovae are powered by the thermonuclear explosion of a white dwarf that accretes matter from a companion star, thereby growing in mass until it approaches the Chandrasekhar mass limit. Important open questions are the nature of the progenitor system and the nuclear processes that lead to the thermonuclear runaway. These questions need to be answered before the problem of the nature of the actual ignition can be addressed in a self-consistent way.

Weak interaction rates during the explosions significantly affect the dynamics of the explosion and the composition of the ejected ashes. Reliable theoretical predictions for electron capture rates, as well as experimental constraints from RIA experiments, are needed to make nucleosynthesis a powerful constraint for Type Ia supernova models. In addition, nuclear burning of the outermost layers in Type Ia supernovae needs to be investigated to clarify whether these events contribute to the synthesis of proton-rich heavy p-nuclei found in nature (see Section D). Developing multi-dimensional hydrodynamic models of Type Ia supernovae comprises the larger astrophysical context which addresses open questions such as nature of the progenitors, ignition processes, flame propagation, and ejected nickel mass. Performing such simulations, with updated strong and weak rates, ties directly to RIA experiments. In addition, nucleosynthesis post-processing calculations of the multi-dimensional thermodynamic trajectories will determine the effect of RIA experimental results on observable isotopic yields.

III.D.4. Understand nova nucleosynthesis

The nova problem is related to the Type Ia supernova progenitor question. Novae are stellar explosions powered by explosive hydrogen burning on the surface of accreting white dwarfs. The explosions repeat with periods ranging from decades to 100,000 years, each time ejecting the entire accreted envelope together with some of the underlying white-dwarf material. The occurrence of novae in an accreting white dwarf system therefore prevents the growth of the white dwarf needed to initiate a Type Ia supernova. Novae are important probes for the structure and evolution of accreting white dwarfs, and it is important to explore the borderline between binary systems that go supernovae and novae. Novae themselves are important contributors to galactic nucleosynthesis possibly responsible for the origin of ^{13}C, ^{15}N, and ^{17}O in nature, and likely contributors to the galactic inventory of radioactive ^{26}Al. Key questions are how novae can accumulate the massive envelopes that they are observed to eject, and related to that, how white dwarf material is mixed into the burning envelope. Again, nucleosynthesis and observed abundances of ejecta, including the possible future detection of γ-ray emission from radioactive decay for example of ^{22}Na, could provide powerful constraints. This requires that the nuclear physics of the proton-rich unstable nuclei participating in explosive hydrogen burning is well understood. Some of these reactions will be measured directly at RIA, but some are out of reach for experimental study and need to be calculated theoretically, or at least be derived from indirect measurements with the help of theoretical reaction models. As direct reaction rate experiments are difficult and take a long time, theoretical calculations are also important to guide experimental efforts, especially at a facility like RIA where beam time will be highly competitive.

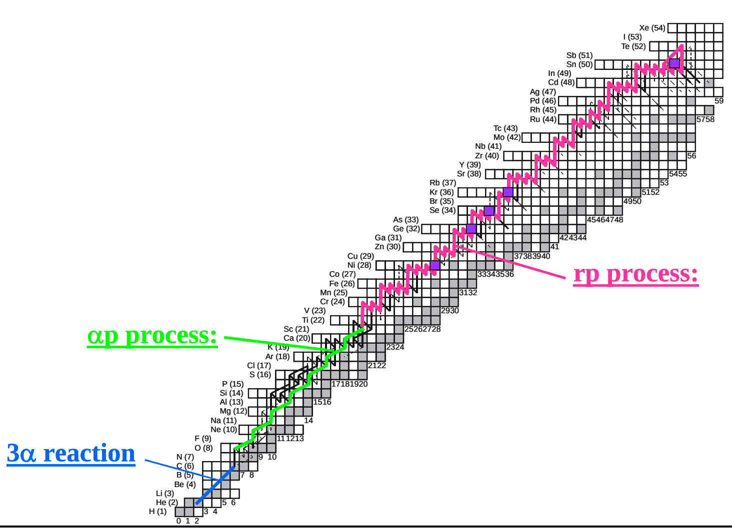

Figure 12: The ap-process and rapid proton-capture process (rp-process) reaction flows powering an X-ray burst.

In the broad astrophysical context, fully self-consistent nova models need to be developed that take into account the evolution of the white dwarf prior to ignition and also include a realistic treatment of multidimenional effects such as mixing and convection. Implementing accurate reaction rates in such calculations and using them for sensitivity studies with realistic nuclear physics uncertainty will directly enhance the scientific return of RIA.

III.D.5. Use X-ray binaries to understand neutron star structure

The final outcome of the death of a massive star is either a neutron star a black hole. Neutron stars provide a unique laboratory for studying the properties of matter under extreme conditions. Open questions include the nuclear equation of state at high densities, in particular the density dependence of the neutron proton symmetry energy, as well as the conditions needed for superfluidity and the formation of exotic phases such as meson or quark condensates. Neutron stars might even be made entirely of strange matter, so called strange stars. Nuclear theory needs to address these fundamental questions directly, and also in terms of experimental observables in heavy-ion collisions that can be studied for stable nuclei at RHIC and for extreme isospins at RIA.

X-ray binaries that contain a neutron star that accretes matter from a companion are a particularly rich source of information on neutron stars. These systems provide a wide range of observables, ranging from thermal radiation, ms oscillations, and absorption lines to bright X-ray bursts and superbursts. These observables are directly powered by a variety of nuclear processes. Understanding the nuclear physics of these processes is a pre-requisite for using them as powerful probes to extract neutron star properties such as mass, radius, magnetic field strengths, spin frequencies, and core cooling rates. Among the most important nuclear processes is the explosive hydrogen and helium burning that powers X-ray bursts and determines the composition of the neutron star crust. The reaction sequence during an X-ray burst proceeds through nuclei at or close to the proton drip line mainly by (p,γ) and (p,α) reactions and beta-decays (rp-process). A statistical description of the proton-induced reactions for nuclei close to the proton drip line is inadequate due to the insufficient density of states. Hence, nuclear reaction models incorporating appropriate nuclear structure have to be developed for extrapolation or prediction of low-energy reaction cross sections and for the extraction of crucial information for such cross sections from indirect experimental measurements. Improved nuclear structure models for the description of beta-decays at finite temperature are also needed.

Advancing X-ray burst calculations, for example, to take into account more physics such as multi dimensional effects, rotation, or diffusion, comprises the larger astrophysical context which addresses open questions such as flame propagation across the surface, oscillations modes, transition from unstable to stable burning, and super-bursts. To enhance the scientific impact of RIA, these calculations need to be used to explore the underlying nuclear processes by incorporating all relevant nuclear physics. Astrophysical X-ray burst models that give light curves are intimately related to the RIA experiments. The light curves are sensitive to the nuclear physics input and place the relevant RIA experimental results into the astrophysical context. In addition, these light curves can be directly compared to observations from high-energy satellite missions. Astrophysical models also need to explore whether some of the synthesized elements in X-ray bursts can be ejected from the neutron star and either can contribute to the element abundances in the Universe or are at least observable spectroscopically. Due to continuous accretion, the ashes of X-ray bursts become incorporated into the crust of the neutron star where it undergoes electron captures, neutron drips, and potentially pycnonuclear fusion reactions. These reactions generate energy, which changes

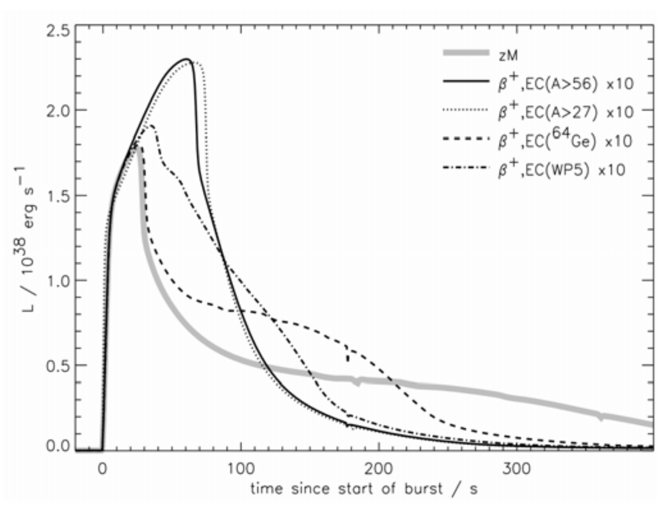

Figure 13: Model calculations of X-ray burst light curves for different choices for the underlying nuclear physics of the rp-process. These choices are all reasonable within current nuclear physics uncertainties, yet they result in vastly different model predictions. ZM represents the standard model.

the properties of the neutron star and are observable as residual luminosity in soft X-ray transients during periods without accretion. Calculations of these crust processes that incorporate RIA nuclear physics are needed to explore the sensitivity of observables to neutron star properties such as crust conductivities, compactness, and the state of matter in the interior. Together with such calculations, results from RIA will allow one to use observations of X-ray binaries to constrain the properties of neutron stars.

III.D.6. Understand low-mass giants and the s-process

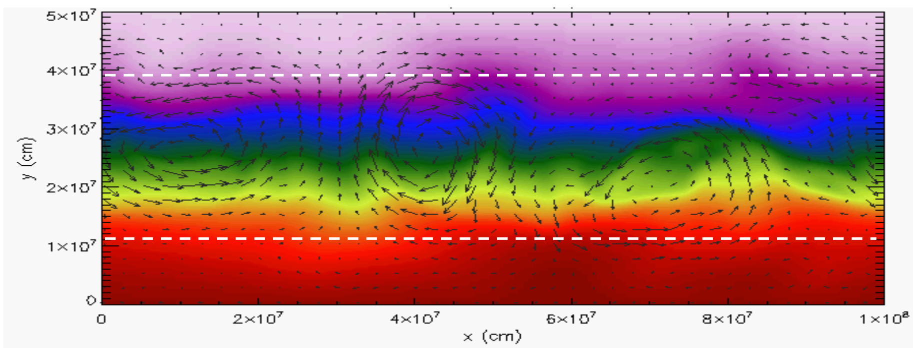

Figure 14: Complicated convective turbulent flows similar to those in nuclear production region in the interior of a star. The colors indicate temperature. Such processes can be experimentally constrained with s-process abundance observations and experiments with a neutron source at RIA. (2D simulation with the ASC FLASH code.)

In the final, advanced phase of evolution, low- and intermediate-mass stars inflate to giant dimension, fueled by nuclear burning of H and He in shells surrounding the electron-degenerate core. These Asymptotic Giant Branch (AGB) stars are the nuclear production site of the slow neutron capture process (s-process). About half of all elements heavier than iron are made by this sequence of neutron capture processes, interrupted by β-decays. In the past, much of the s-process nuclear physics involving experimental work with stable beams and targets has been completed. Simultaneously, a better theoretical understanding of the thermodynamic evolution of AGB stars has been developed. However, the main uncertainties are still the mixing processes, in particular at convective boundaries, and those induced by rotation and magnetic fields. These uncertainties impede accurate chemical yield predictions for stars of all masses, as well as the initial models for supernova explosions.

Branching points in the s-process in AGB stars provide a method to better understand the physics of mixing in stars. Branchings are radioactive nuclides where stellar β-decay and neutron capture times are comparable. The branching ratio depends then on the thermodynamic conditions and on the uncertain mixing processes. The branchings determine isotopic as well as some elemental ratios in the stellar ejecta. These are observable in stellar spectra or can be measured in presolar grains. Comparison of these astrophysical observables with model predictions directly tests the model assumptions including mixing mechanisms. This method of using the s-process on radioactive nuclides as a diagnostic tool can significantly improve our understanding of the conditions at the nuclear production sites in stars in general. However, accurate capture cross sections and β-decay half-lives of the involved unstable nuclides are absolutely necessary for this approach.

Some of the potent cases in this context can only be measured with a neutron facility in conjunction with radioactive target production at RIA. Nuclear theory is needed to complement the experimental data to provide accurate cross sections over the entire relevant energy range. Nuclear theory is also needed to calculate corrections to neutron capture rates and beta decay half-lives due to the stellar environment.

IV. Summary: Challenges and Opportunities

RIA theory covers a range of activities from nuclear structure and reactions, to nuclear equation-of-state issues. Furthermore, many nuclear issues are relevant to processes in astrophysical environments. Since all nuclei heavier than carbon are made in stars, this synergy is, in fact, natural. Understanding both the basic nature of the nuclear many-body problem and understanding the effects of nuclear physics on stellar evolution and nucleosynthesis constitutes major intellectual efforts. Furthermore, low-energy nuclear science remains important in matters of national safety and security.

The previous chapter describes a number of theoretical challenges that must be met during the next decade in order to facilitate the success of an experimental program focused on short-lived isotopes. These efforts include:

- Development of ab initio approaches to medium mass nuclei.
- Development of self-consistent nuclear DFT methods for static and dynamic problems.
- Development of reaction theory that incorporates relevant degrees of freedom for weakly bound nuclei.
- Exploration of the isospin degrees of freedom of the density-dependent nuclear force.
- Development and synthesis of nuclear theory, and its consequent predictions, into various astrophysical models to determine the nucleosynthesis in stars.

Present research facilities and projected upgrades to them, and the future RIA experimental facility, are measuring, or will measure, nuclear structure and reactions for nuclei that have very short half-lives and live close to the neutron (or proton) drip line. Many of these experiments will be relevant to astrophysics and will enable a comparison of theoretical predictions to experimental data. There will be numerous (in fact, many) nuclei and nuclear properties that we cannot measure. For an understanding of those systems, a robust nuclear-theoretical capability is required.

Certain critical investments in nuclear theory research over the last 10 years are yielding significant knowledge and understanding of properties of nuclei. Continued success will require investments in the following areas.

- Several approaches to the nuclear many-body problem have enabled both few- and many-body calculations to proceed in an ab initio way, starting from the basic two- and three-nucleon interactions. Critical investments for nuclear theory will include extensions of ab initio techniques to heavier nuclei and drip-line systems.
- Self-consistent mean-field theories offer a robust and global approach to a wide range of nuclei and nuclear properties. Critical to the success of this endeavor will be a full description of the energy density functional, and the development of methods to treat excited states and giant resonances on the same footing.

- The treatment of the continuum in both structure and reaction theories has been, and will continue to be, a critical area that requires both new ideas and potentially new computational techniques in order to be successfully applied to nuclear scattering of near-drip-line nuclei.
- An understanding of the isospin dependence of the nuclear equation of state will be an important outcome of the medium-energy collision work performed at RIA. Theorists also need to develop methods to extract from experimental data relevant quantities that will enable a description of the nuclear equation of state.
- The interplay of astrophysics and low-energy nuclear theory requires some level of coordination. This is taking place through two supernova SciDAC efforts for nuclear physics relevant to supernova production. We identified several other astrophysically interesting sites that would benefit from nuclear theory input.

While significant progress on the basic theoretical underpinnings of the nuclear many-body problem will require an enhanced workforce development and research effort, one challenge will be to export the knowledge gained from these research activities to the broader nuclear physics and nuclear astrophysics communities. One component of future research will be to assess the validity of models used in nuclear science applications (for example, in nuclear astrophysics), and that assessment hinges on our ability to perform calculations in ever larger nuclei and in nuclei far from stability.

We also identified several important areas and elements of theoretical nuclear astrophysics that should be actively supported. Each scientific area involves interdisciplinary challenges for both nuclear theory and astrophysics theory. Progress requires mutually beneficial and coordinated research in theoretical astrophysics and nuclear physics. This will allow us to combine leading-edge nuclear physics with the latest astrophysical models to answer the major open questions in nuclear astrophysics.

Appendix: development of this report and its authors

The RIA Theory Bluebook was generated by the RIA Theory Group at the direction of the RIA Theory Group Executive Committee. Executive committee members are:

- David J. Dean, Chair (ORNL)
- Jacek Dobaczewski (Warsaw)
- Karlheinz Langanke (GSI)
- Filomena Nunes (MSU)
- Erich Ormand (LLNL)

A meeting of the full RIA Theory Group was held in Chicago on October 31, 2004 to begin the process of writing. At that meeting, summary talks of the current status and future directions were given by Witek Nazarewicz (nuclear structure), Phillip Chomaz (nuclear reactions), and Yong Qian (nuclear astrophysics). A writing team was also established at the Chicago meeting. Dean served as editor of the Bluebook. The members of these teams are:

- Nuclear Structure
    - George Bertsch (University of Washington)

  - Dick Furnstahl (Ohio State University)
  - Witek Nazarewicz (University of Tennessee/ORNL)
  - Erich Ormand (LLNL) (Coordinator)
- Nuclear Reactions
  - Philippe Chomaz (GANIL)
  - Pawel Danielewicz (Michigan State University)
  - Bao-An Li (Arkansas State University)
  - Filomena Nunes (Michigan State University) (Coordinator)
  - Ian Thompson (Surrey)
  - Daniel Baye (Brussels)
- Nuclear Astrophysics
  - Karlheinz Langanke (GSI, Darmstadt)
  - Hendrik Schatz (Michigan State University) (Coordinator)
  - Chris Fryer, Alexander Heger, Falk Herwig, and Frank Timmes (LANL)
- Interdisciplinary Science
  - Alex Brown (Michigan State University) (Coordinator)
  - Vladimir Zelevinsky (Michigan State University)
  - David Dean (ORNL)

Chairs of the various writing sections held regular teleconferences during the course of the writing of the document.

Once written, the report was posted on the web for a period of 3 weeks for open comment from the RIA Theory Group. The writing group incorporated comments from the community into the document. Final publication occurred in May 2005. The bluebook will reside on the RIA Theory Group web page at www.orau.org/RIATG/.

FIGURE CREDITS

- Figure 1: Provided by Steven Pieper and the GFMC collaboration, Argonne National Laboratory
- Figure 2: “Shape coexistence and triaxiality in the superheavy nuclei”, S. Cwiok, P.H. Heenen, and W. Nazarewicz, Nature 433, 705 (2005).
- Figure 3: Courtesy W. Nazarewicz, University of Tennessee
- Figure 4: Provided by Ian Thompson, University of Surrey
- Figure 5: Provided by Ian Thompson, University of Surrey
- Figure 6: Provided by Jim Al-Khalili, University of Surrey
- Figure 7: “Determination of the equation of state of dense matter”, P. Danielewicz, R. Lacey, and W.G. Lynch, Science 298 1592 (2002). Figure 1.
- Figure 8: Provided by B. O'Shea, astro-ph/0503330
- Figure 9: Provided by C. Freyer
- Figure 10: Provided by K.-L. Kratz
- Figure 11: Image from D. H. Lumb (ESA)
- Figure 12: Provided by H. Schatz.
- Figure 13: Provided by A. Heger.
- Figure 14: Provided by A. Heger and F. Herwig